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TAMPERE UNIVERSITY OF TECHNOLOGY

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PASSIVE UHF RFID TAG FOR WIRELESS DETECTION OF  
COMPRESSION OF MATERIALS  
Master of Science Thesis

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## ABSTRACT

**Shoaib Tahir Qureshi:** Passive UHF RFID Tag for Wireless Detection of Compression of Materials  
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Starting from assets tracking, inventory control and identification applications, RFID systems are becoming a backbone for wireless sensor networks (WSNs). Due to their small size, low cost and low maintenance, they are very suitable choice for future advancements in Internet of Things (IoT) technology. Passive wireless sensors have an advantage over active sensors as they don't require any external power source for their operation as active sensors require a battery or any other source to operate. The demand of RFID passive sensors is increasing as new research areas are opening whether it is a wearable technology application, or it is related to health monitoring.

In this research work, RFID pressure sensing application has taken into consideration. Two different types of antennas were used for testing purpose in order to get a suitable one out of it. Two-part dipole antenna and SRR antenna were selected as some of the previous work has been done on these antennas. Two-part antenna concept for both, the dipole and SRR used here is to analyze the sensor response when it is subjected to different compression levels. Performance of both antennas were analyzed in order to see which of the antenna's read range is increasing when compression level is increased.

With SRR, there was an increase in read range of the tag as compression was done, compared with a two-part dipole antenna which behaved in a random manner. We got successful results from SRR, but the two-part antenna didn't work the same way. Similarly, the backscattering was also observed on SRR to further improve the results and analysis. We named our tag with SRR antenna a 'Sensor Tag'. In terms of backscattering power, sensor tag was taking a less amount of power to turn it on compared with a state when the sensor was uncompressed.

Performance of a sensor tag was also evaluated when a reference tag was inserted in anechoic chamber with a sensor tag. Reference tag showed higher read range with almost a same behavior in all of the states when the sensor was compressed. Similarly, backscattering measurements were also performed to conclude that SRR when used as a sensor tag in compression state behaves well compared with a two-part dipole antenna.

## **PREFACE**

This Master's thesis, "Passive UHF RFID tag for wireless detection of compression of materials" is carried out in fulfilling the requirements of a Master's degree in Electrical Engineering with a major in 'Wireless Communications'. All the research work during this thesis has been conducted under Wireless Identification and Sensing Research Group (WISE). I would especially like to thank my thesis supervisors, Dr. Toni Björninen and Dr. Johanna Virkki who has given me this topic as my Master's thesis and supported me throughout the completion of this work.

I would like to thank all mighty Allah who has given me this opportunity to pursue my Master's degree here in Tampere University of Technology, Finland.

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Tampere, Finland

Shoaib Tahir Qureshi

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## LIST OF SYMBOLS

$E$	Electric Field [V/m]
$H$	Magnetic Field [A/m]
$E_x$	Electric Field on x-axis
$E_y$	Electric Field on y-axis
$RL$	Return loss [dB]
$D$	Directivity [dBi]
$G$	Gain of an antenna [dBi]
$\Gamma$	Reflection Co-efficient
$P_t$	Transmitter Power [dBm]
$P_r$	Receiver Power [dBm]
$G_t$	Transmitter Gain
$G_r$	Receiver Gain
$S$	Power Density [ $W/m^2$ ]
$A_e$	Effective Aperture
$\lambda$	Wavelength [m]
$\pi$	Mathematical constant
$R$	Distance between Transmitter and Receiver [m]
$Z_L$	Load Impedance [ $\Omega$ ]
$Z_S$	Source Impedance [ $\Omega$ ]
$Z_A$	Antenna Impedance at terminals [ $\Omega$ ]
$X_A$	Antenna Reactance [ $\Omega$ ]
$R_A$	Antenna Resistance [ $\Omega$ ]
$j$	Complex value
$U$	Radiation Intensity [W/unit solid angle]
$U_o$	Radiation Intensity of an isotropic source [W/unit solid angle]
$P_{in}$	Total input power [dBm]
$P_{rad}$	Total radiated power [dBm]
$e_{rad}$	Radiation Efficiency
$L$	Length of plywood
$W$	Width of plywood
$H$	Height of plywood
$R$	Radius of plywood
$L_s$	Length of sponge
$H_s$	Height of sponge
$W_s$	Width of sponge
$C_{comp}$	Space to provide compression
$r_{tag}$	Read Range [m]
$k$	Constant Factor that affects the read range
$\theta$	Altitude in spherical coordinates
$\emptyset$	Azimuthal angle in spherical coordinates
$p$	Polarization efficiency
$\tau$	Co-efficient of impedance matching
$P_{th}$	Power threshold sensitivity [dBm]
$Z_a$	Antenna Impedance
$Z_c$	Chip Impedance
$\chi$	Polarization matching co-efficient



## LIST OF ABBREVIATIONS

UHF	Ultra-High Frequency
RFID	Radio Frequency Identification Technology
EPDM	Ethylene Propylene Diene Monomer
SRR	Split Ring Resonator
IoT	Internet of Things
SHM	Structural Health Monitoring
EIRP	Effective Isotropic Radiated Power
RCS	Radar Cross Section
IFF	Friend and Foe System
dB	Decibel

# 1. INTRODUCTION

With the progress of time and technology, RFID systems are making a strong impact in the evolution of the IoT [1], which is now making its way to ‘Massive IoT’. A complete RFID system includes a reader, a tag, and a back-end computer. There are three main categories of tags in terms of power; active, semi-passive and passive. Passive UHF RFID tags are most important and are widely used because of their battery-free operation where a tag gets power from reader. The frequency range of these systems is 860-960 MHz. For a long time, RFID technology has been used for detection purposes for humans, animals, objects and several other tracking applications. But these days, RFID-sensing is making a huge impact on sensor networks with several application areas in wearable technology, implanted devices and structural health monitoring etc.

Bending and stretching of RFID tags have been studied a lot but the compression of materials has not given that much of focus. The focus of this research was to implement such a sensor tag that can be used to analyze the performance of two different antennas when they are apart and then brought closer to each other as the sensor is compressed. Further, the addition of a reference readout will provide a way to measure the response of sensor tag in a multipath propagation environment. Passive sensors have ability to provide sensing without using any external power source. RFID pressure sensing can be useful in several applications like counting and tracking of people while they sit on chairs in an auditorium or classrooms. In the same way they can be used in patient’s bed or pillow in order to monitor whether the patient is laying on the bed or not. The combination of RFID and sensor technology is taking us into the world of new research areas [2]. The battery-free operation of RFID based passive sensors are having huge number of applications in implantable medical devices and it has increased over the past decade. It is one of the evolving and rapidly growing wireless communication technologies with low cost and better flexibility. Advancements in RFID technology with sensor integration is a huge step towards implantable RFID tags [3]. These systems will be cost effective as there can be only one reader which can basically get information from several sensors at a same time. Data collection from many sensors will make a huge impact for monitoring the systems intelligently [4]. This will add new research areas in the field of Patient health monitoring where RFID sensor tags can be used to get patients updates on their current condition.

In this thesis work, two different types of antennas were used for wireless detection of UHF RFID tag in different compressed states. SRR Antenna and Two-part Dipole Antenna were used to study and analyze the compression property on both of them. Copper was used for designing antennas and the substrate material was EPDM (Ethylene

Propylene Diene Monomer) with a 2 mm thickness. Further, for providing compression, a sponge was used, and both the fabricated antenna parts were separately placed on different sides of the sponge. A frame of plywood with nuts and bolts was used for providing sensor compression. The concept of experimentation was to study the effect of compression on read range and how much backscattered power reaching the reader antenna.

This Master's thesis is followed in this way: **Chapter 2** is about antenna fundamentals where its basic parameters are briefly discussed. Introduction to RFID systems with an overview to passive UHF RFID is also explained here. **Chapter 3** includes RFID sensing and its connection to IoT. It also has challenges that occur in implementation and the motivation behind this research work. Measurements and Results comes in **Chapter 4** along with analysis of results. **Chapter 5** has conclusion followed with a publication which is accepted in IEEE RFID-TA 2018.

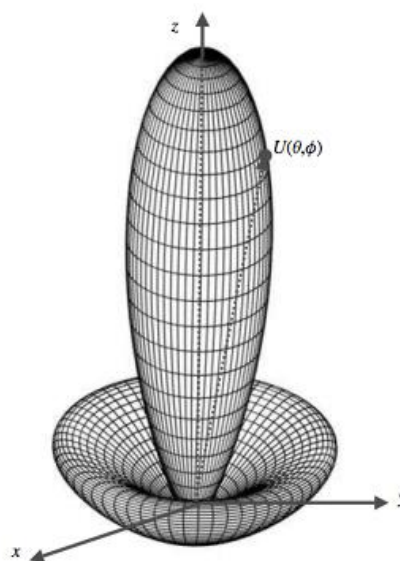
## 2. BACKGROUND STUDY

### 2.1 Antenna Fundamentals

An antenna is a device that converts one form of energy to another form. An antenna on transmitting side converts electrical energy into radio waves while the receiver antenna works in an opposite way; radio waves into electrical energy. Design of RFID tag antennas requires some important concepts which needs to be taken into consideration. These are briefly discussed here:

#### 2.1.1 Radiation Pattern

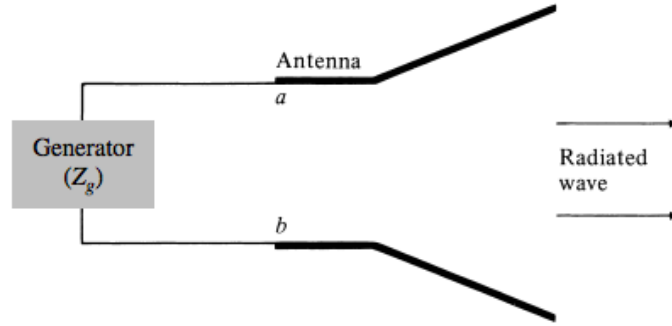
The graphical representation of power radiated or received by an antenna is said to be its radiation pattern [5]. Radiation pattern of an antenna describes its radiation properties with respect to space coordinates. The power density drops by  $1/r^2$  when the distance between transmitting antenna and receiving antenna is large, as of many wavelengths. The power density is varied with the angular position which can be represented as a radiation pattern of an antenna. This variation of power density depends on the type of antenna and how it is designed. The radiation pattern of both, the transmitting antenna and a receiving antenna can be same if there are no reciprocal components in an antenna [6]. There can be different lobes in radiation pattern of an antenna showing the amount of field strength. Below is a 3-dimensional radiation pattern of an antenna showing its main lobe which is the area having most of the radiated power. There can be other side lobes as well which are the ones having unwanted radiations.



**Figure 1.** 3D Radiation Pattern of an Antenna [7]

### 2.1.2 Input Impedance

The ratio of voltage and current at an antenna's input port is said to be its input impedance. There are two parts of antenna's input impedance; real part and imaginary part. 'Radiation resistance' and 'loss resistance' comes in real part and imaginary part consist of 'Antenna Reactance' [8].



**Figure 2.** *Transmitting Antenna [7]*

Assuming that if there is no load attached to an antenna, the input impedance here can be written as:

$$Z_A = R_A + jX_A \quad (2.1)$$

### 2.1.3 Directivity and Gain

Directivity is a concentration of radiation intensity in a certain direction [9]. It tells how well an antenna is radiating in a specific direction. Both directivity and gain are related to the concentration of energy in a certain direction. Directivity of an antenna is totally based on the shape of radiation pattern and it doesn't consider any power losses. As, the radiation intensity of an isotropic source is:

$$U = \frac{P_{rad}}{4\pi} \quad (2.2)$$

where,  $P_{rad}$  is total radiated power. Now, directivity can be expressed as:

$$D = \frac{U}{U_o} = \frac{4\pi U}{P_{rad}} \quad (2.3)$$

Directivity only tells about the directional capabilities of an antenna but gain also includes an antenna's radiation efficiency. The size of an antenna depends on the

antenna gain as well as on how the antenna's structure is optimized. To express the gain of an antenna, these losses should be considered:

$$G = \frac{4\pi U(\theta, \phi)}{P_{in}} \quad (2.4)$$

where,  $P_{in}$  is the total input power which is accepted,

$$P_{in} = \frac{P_{rad}}{e_{rad}} \quad (2.5)$$

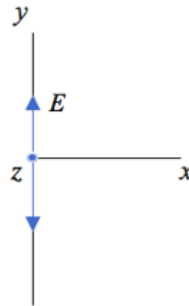
$e_{rad}$  is the radiation efficiency which is the amount of power that is lost in an antenna which results in the reduction of power radiated by an antenna. Typically, radiation efficiency ranges from 0.6 to 0.95 [10].

#### 2.1.4 Antenna Polarization

Antenna polarization describes the orientation of field in a specific direction. Selecting the type of polarization for RFID antennas depends on the type of application in which we are going to use that antenna. Antenna polarization can be of three types:

- **Linear Polarization**

Polarization is said to be linear if an antenna is radiating in one specific direction. This is the most commonly used polarization for antennas and have the highest read range due to the concentration of the field in one particular direction.

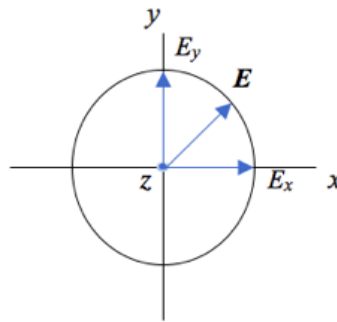


**Figure 3.** Linear Polarization

- **Circular Polarization**

A special type of elliptical polarization in which a signal completes a 360-degree rotation once every period [11]. Circular polarization (CP) can be of two types, right hand circular polarization (RHCP) and left-hand circular polarization (LHCP). The only difference between these two is their different polarization sides. They have smaller read ranges compared to linearly polarization antennas because of the 3dB power splitting in two planes.

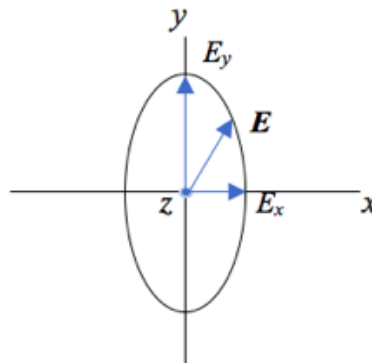
Linear and circular polarizations are used more compared to elliptical ones.



**Figure 4.** Circular Polarization

- **Elliptical Polarization**

Polarization is elliptical if both the vertical and horizontal elements in the same place gets out of phase with unequal magnitudes and a  $90^\circ$  phase difference [12]. Here, electric field follows an ellipse manner which can be seen from the figure below:



**Figure 5.** Elliptical Polarization

### 2.1.5 Return Loss

In order to transfer all of the power from input to output, source impedance and input impedance should be matched perfectly [5]. On the other hand, if they are not perfectly matched then we have a case where some or most of the energy is reflected back, which is called as antenna's return loss:

$$RL = -20 \log |\Gamma|_{(dB)} \quad (2.6)$$

where,

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} \quad (2.7)$$

' $\Gamma$ ' corresponds to the reflection co-efficient. Whenever, the return loss is high, it means that we have good matching between an input impedance and a source impedance.

## 2.2 Friis Transmission Equation

Friis transmission equation is an equation that tells how much power an antenna has received from another antenna in ideal conditions. It is a very helpful equation in terms of studying and designing RF communication links.



**Figure 6.** A Simple Radio Communication Link

Considering the above communication link, if both antennas are aligned to each other, then the receiver antenna has a power density 'S':

$$S = \frac{P_t G_t}{4\pi R^2} \text{ W/m}^2 \quad (2.8)$$



The effective aperture of an antenna can be expressed as:

$$A_e = \frac{\lambda^2 G_r}{4\pi} \quad (2.9)$$

Here, effective aperture of an antenna describes how efficiently a receiver antenna is accepting RF energy which is being transmitted.

Power collected at receiver antenna will be:

$$P_r = S A_e \quad (2.10)$$

Now, combining above equations of power density and effective aperture, total received power can be calculated as:

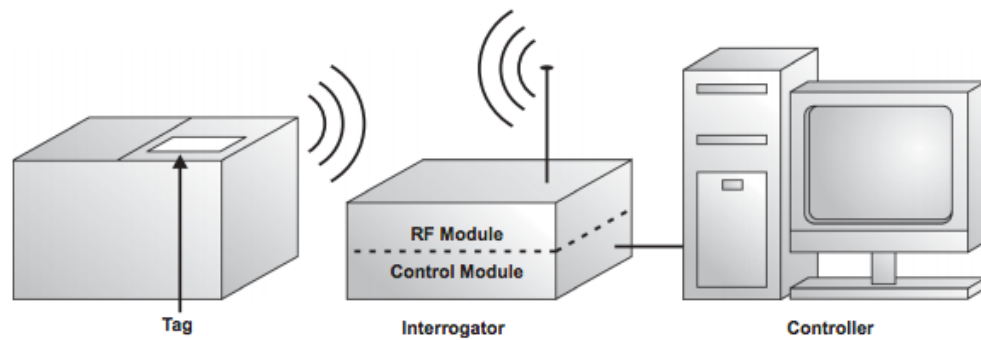
$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi R)^2} \quad (2.11)$$

## 2.3 Radio Frequency Identification Technology

### 2.3.1 Introduction to RFID

RFID is not a new technology, it was first started in 1948 by Harry Stockman [13]. The main idea related to signaling procedure was actually started from the World War II named ‘friend and foe system (IFF)’ where main problem was of identification between different planes [14]. RFID is a technology in which Radio Frequencies (Electromagnetic waves) are used as a medium for wireless identification or for the purpose of data transfer. Identification can be of anything like people, animals and objects. RFID is in a mainstream these days because of its many advantages over previously used technologies like barcode. RFID has removed the need of a line-of-sight (LOS) link between a reader and a device that needs to be read. As with the increase in research areas, it can be said that RFID technology is a combination or a convergence of three other technologies including RF Electronics, IT and material sciences [15]. With a numerous growth and advancements in RFID technology, now it is in a mainstream where academic institutions and industries are working in collaboration to make it a reliable and promising future technology.

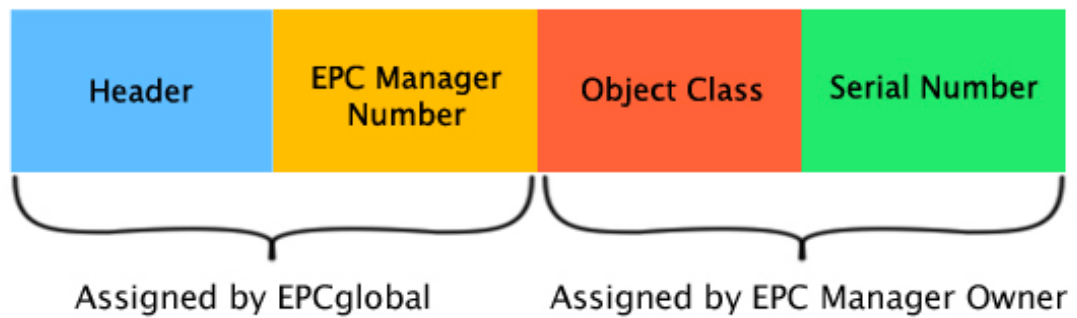
Figure below shows a simple RFID system comprising of a tag and a reader with a computer system connection:



**Figure 7. Simple RFID System [15]**

There are several advantages that RFID technology has over past or previously used identification technologies like bar code where a line of sight is must between a barcode reader (scanner) and an object on which barcode is written. These barcodes can be scanned or identified just one time compared with RFID tags, where several reads can occur as far as the tagged object remains in the range of reader. These days, RFID is also known as a ‘short-range IoT’ technology. It has two main parts including a reader and a tag having connection with a server forming a complete system. RFID tag itself has two parts consisting of an antenna that is used to transmit and receive radio waves and an integrated chip which has tag’s specific ID and information stored in it [16]. These chips are also called ASIC chip which stands for application specific integrated chip. The basic or main function of tag is to transfer information that is stored in the memory chip. The size, shape and type of an antenna for RFID tag depends solely on the targeted application. The IC is connected to the tag antenna and that tag antenna is printed or manufactured on the substrate material. There are various substrate materials but most importantly a flexible material is used like EPDM is used in this work. There might be an effect of substrate material on the performance on an antenna, so that should be kept in mind while designing an RFID tag.

RFID readers are main part of the system which are interrogators and act as a brain of RFID system and provides a bridge between the tags and controlling device. It consists of an RF module that controls communication part and control module is for connecting it to controller. Antennas are connected to readers in order to transmit or receive interrogating signals. They also perform some other functions including encryption of data and reading/writing data on tags. There can be different coding and modulation schemes for a data communication between a reader and a tag.



**Figure 8.** Basic Format of EPC number [17]

There are two main organizations that provide standards for RFID systems which are:

- EPC (Electronic Product Code) Global
- ISO (International Standards Organization)

Both of these organizations work in collaboration for providing specifications to remove the worldwide compatibility issues in implementation of RFID systems. EPC global has standardized EPC number which includes header, unique identifier and has a filter value [18].

Integration of sensors in RFID technologies these days have opened new application areas in academic research as well as in industrial applications. With that, RFID is not limited for just tracking and identification purposes but also have extensive applications in medical sector providing an ease for doctors to efficiently manage and monitor patient's health and recovery in the form of implanted sensors [19].

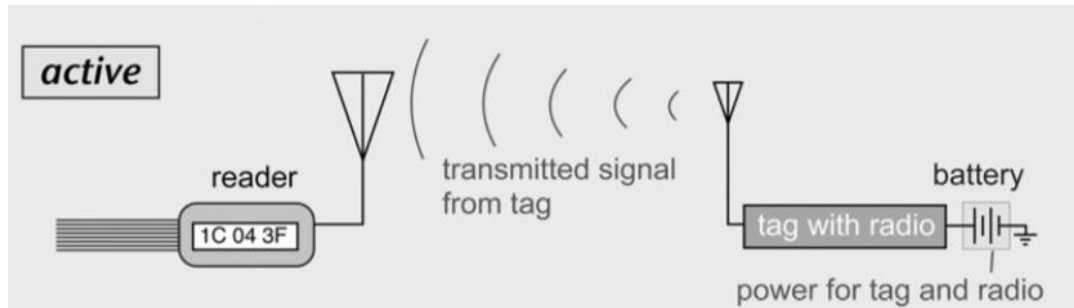
### 2.3.2 Types of RFID systems

RFID tags can be categorized in different ways. There are tags that are read-only (RO) tags which are like barcode and nothing can be re-written on them. On the other hand, there are tags that can be re-programmed which means, read or write function can be applied to them. They are called read/write (RW) tags. Depending upon the type of power an RFID tag is using, there are three types of RFID tags which are explained below:

- **Active Tags:**

A classification of RFID tags in which an external power source is required to turn on the tag. This external source can be a battery as well that is used to transmit information from the tag to reader [20]. These tags are usually bigger in size and are much complex than other RFID tags. Because of their dependence on external source, their lifetime is limited compared to others. Active tags are most expensive ones as well, but they have longest

read ranges among all. They have many applications in high level tracking of machines, vehicles, containers and are commonly used in military assets. A transponder connected to an aircraft is an example of an active tag.

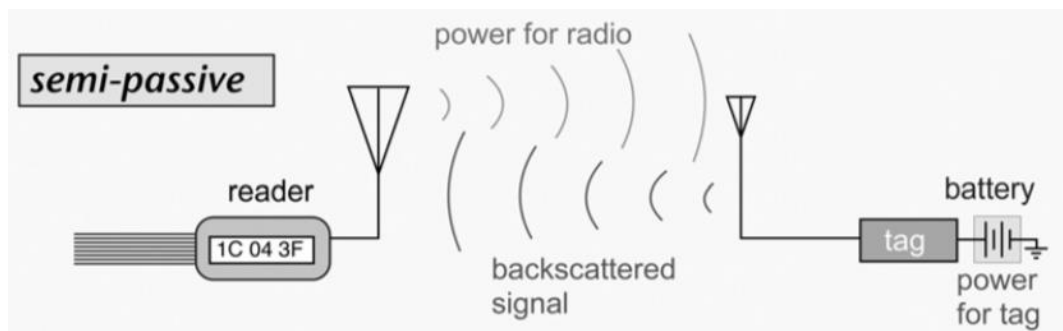


**Figure 9. Active Tags Configuration [21]**

- **Semi-Passive Tags:**

Tags in which an external power source is required to turn on the tag circuitry. They can have a battery as an external source in order to communicate with a reader.

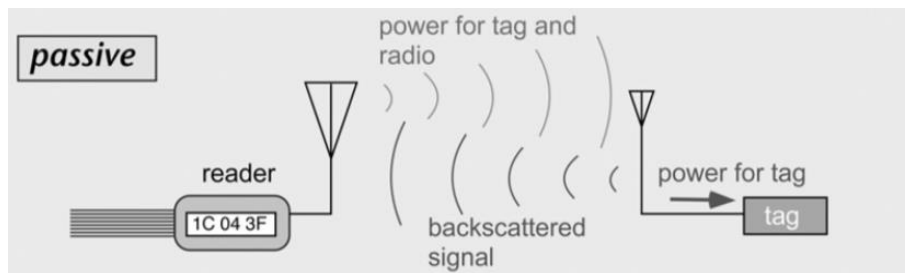
Backscattered signal is used in order for the tag to communicate with reader. External source in these tags helps to increase the communication range. They have several industrial applications in sensing and tracking high value assets. Figure below shows the configuration of a semi-passive device.



**Figure 10. Semi-Passive Tags Configuration [21]**

- **Passive Tags:**

Passive RFID tags doesn't require any external power supply for its operation. It gets active when it receives RF signal from the reader and starts communicating with the reader via backscattering phenomena. They are the cheapest choice and are very suitable for short range applications. Application includes inventory control, objects and animals tracking, access cards, NFC and several others [22]. The size of passive RFID tags is much smaller than active and semi-passive tags.



**Figure 11. Passive Tags Configuration [21]**

### 2.3.3 Frequency Bands

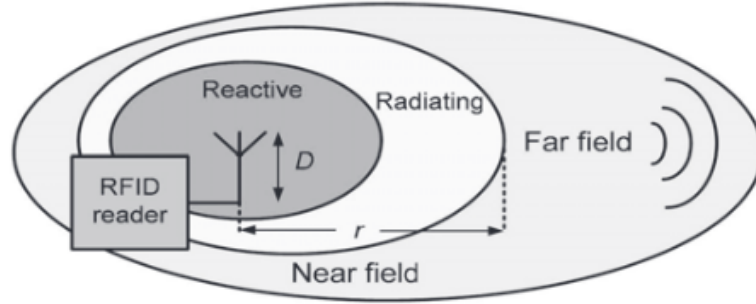
RFID systems use various frequency bands for their operation and these frequency bands are classified on the basis of regions of operation and the type of application. UHF RFID spectrum has different allocations for regions involving North America, Europe, China and Japan, Australia and New Zealand. For European countries the licensed band in this range is 865-868 MHz with some restrictions. Following is the generalized table that shows the operating frequency bands with their range:

<i>Type</i>	<i>Frequency band</i>	<i>Range</i>
<b>LF</b>	125 kHz or 134 kHz	10 cm
<b>HF</b>	13.56 MHz	1 m
<b>UHF</b>	860-960 MHz	10 m-15 m

**Table 1. RFID Frequency Bands**

### 2.3.4 Antenna Field Regions

The space around an antenna can be divided into two main regions, near-field region and far-field region. Further classification of near-field can be done in terms of reactive and radiative near field which can be seen from the figure below:



**Figure 12.** Field Regions of an Antenna [23]

- **Reactive Near-Field:**

The region closest to the antenna is called reactive near-field. **E** and **H** are not in phase in this area and most of the energy is absorbed as it's not radiated outwards. The coupling technique between the reader and tag circuitry here is capacitive as both are very close to each other.

$$r = 0.62 \sqrt{\frac{d^3}{\lambda}} \quad (2.12)$$

- **Radiative Near-Field (Fresnel-Region):**

The region next to the reactive field is a region where most of the energy radiated is said to be a radiative field, also called as a Fresnel region. Here, electric and magnetic fields are in phase.

$$r = \frac{2d^2}{\lambda} \quad (2.13)$$

- **Far-Field (Fraunhofer-Region):**

A field which is far away from the antenna is known as far field or Fraunhofer region. Both **E** and **H** remains in phase and are perpendicular to each other and to the propagation direction. Far-field is the regions that describes antenna's radiation pattern. Following condition express that the antenna is operating in far-field:

$$r = \frac{2D^2}{\lambda} \quad (2.14)$$

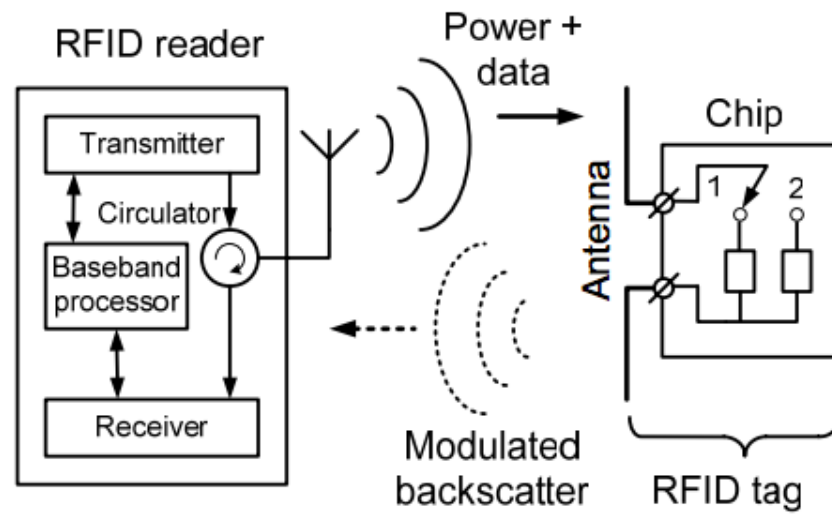
where,  $R \gg D$  and  $R \gg \lambda$

### 2.3.5 Passive UHF RFID

Passive UHF RFID systems first started in 1970's when a range of several meters was achieved. After that there has been a tremendous growth in the development of UHF RFID systems. Different countries have their own frequency band for UHF RFID ranging between 860 MHz to 960 MHz which is an EPC global standard [24]. In passive RFID systems, tag gets power from the RF signal transmitted by the reader antenna. The tag sends the data to RFID reader by switching its input impedance between two states and thus modulating the backscattering signal [25].

There are two distinct wireless communication links between RFID reader and tag. Forward link is from reader to tag in which reader transmits RF energy in order to get response from the tag. Reverse link which is actually called backscattering communication which is from tag to reader where the information stored in the chip is transferred to the reader [26]. Impedance matching between the antenna and the chip is of most importance in passive RFID systems in order to turn on the chip or to get a response from it [27].

There are several application areas of Passive UHF RFID systems more specifically in near-field communications. High data rate, low cost, low power consumption and reduced size makes more efficient for near-field communication systems [28]. Passive behavior of RFID systems leads them to a very suitable solution for sensor applications specifically in the areas of health monitoring and integrating these sensors in wearable electronics technology. Integrated electronics and wearable RFID technology are collectively making a huge impact on the development of a wireless body area networks which are going to be very useful in health, welfare and sports related applications.



**Figure 13.** *Passive RFID System [25]*

The above figure shows the basic working of a passive RFID system. The two main parts of the system includes 'RFID reader' which works as a base station and then RFID tag which is to be attached to any of the objects, people or animals that needs to be identified. The reader consists of a transmitter to send RF signals and receiver to receive signals back from the tag in terms of a modulated backscattered signal.

Few examples of Passive RFID tag antennas manufactured with conductive thread and nickel copper with EPDM (having 2mm thickness) as a substrate are shown below:



(a)



(b)





(c)

**Figure 14.** (a) Two-Part Dipole Antenna (b) Single-Part Dipole Antenna (c) Folded Dipole Antenna

- **Read Range Concept:**

Read Range is a parameter that is used to define the maximum distance in which an RFID tag can be detected (read or write). This distance is actually measured between the reader and the tag. Typically, the read range of Passive UHF RFID system is 1 meter to 3 ft, but it can be higher for Gen2 tags. As there are two links, Reader-to-tag which is a forward link and tag-to-reader which is a reverse link. The forward read range can be calculated as discussed in [29]

$$r_{tag} = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G p \tau}{P_{th}}} \quad (2.15)$$

where,

$P_t$  and  $G_t$  represent the power and gain of transmitter which collectively is EIRP.  $p$  is polarization efficiency and  $\tau$  is the co-efficient of impedance matching between the chip and the tag antenna.  $P_{th}$  is the power threshold sensitivity of the chip.

Above relations can be used to calculate the forward read range. Active tags have the highest read range due to a separate power source on the tag side compared with passive tags. In semi-passive tags, the reader's sensitivity may become a limiting factor for the read range. There are several factors on which the read range depends including tag orientation, type of the reader, antenna gain, antenna polarization and environmental factors etc.

### Performance limitations of Passive UHF RFID

Tag read range is the most important performance criteria. So, following are the main factors that affects the read range of the passive UHF RFID tags:

- **Chip sensitivity:**

Chip sensitivity is the most important limiting factor for RFID tags. It describes the amount of minimum power to turn on the chip. It should be lower in order to have a higher read range.

- **Antenna gain:**

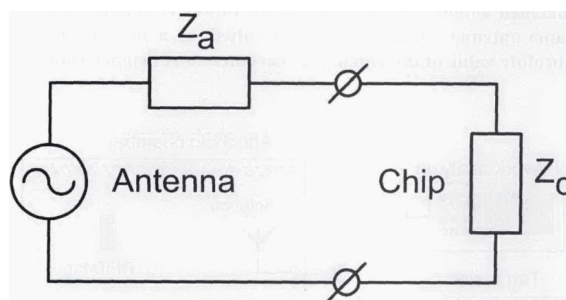
Another important limitation factor for tag read range is 'Antenna Gain'. Tag read range is highest where the antenna gain is maximum.

- **Antenna Polarization:**

Polarization of tag antenna and RFID reader antenna should be identical, or the RFID reader antenna should have circular polarization to achieve higher read range. There is a co-efficient called 'Polarization matching' which is used to characterize the matching between the tag antenna and the reader antenna. It is denoted as ' $\chi$ '.

- **Impedance matching:**

Impedance matching has a direct effect on the performance of an RFID system, most importantly to the range of a tag. The impedance of the RFID chip and the antenna should be matched in order to have a maximum power transfer which results in higher read range of the tag.



**Figure 15.** *Equivalent Circuit of an RFID tag [25]*

In above equivalent circuit of an RFID tag, there is a direct connection of an antenna having an impedance ' $Z_a$ ' with a chip having an impedance ' $Z_c$ '. The circuitry of the chip requires a certain amount of power level to turn itself on.

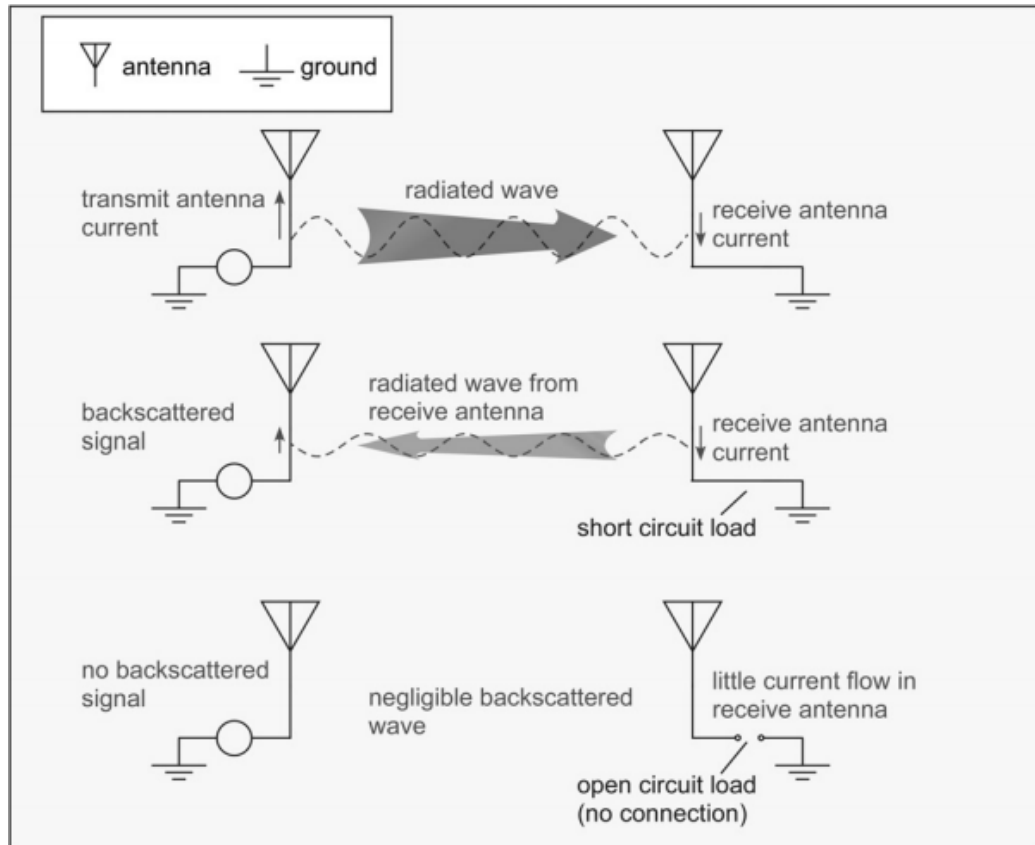
- **Propagation Environment (Path loss):**

Propagation environment also has an effect on the read range of the tag. Environment can be generically categorized as a LOS (Line of Sight) and NLOS (Non-Line of Sight). In case of LOS, there is a straight link between the reader and the tag but in the case of NLOS, there are multiple reflections in a propagation environment which degrades the signal quality eventually lowering the tag's read range [30].

Transmitter power also plays an important role in determining the read range of passive RFID systems as the tag solely depends on the power transmitted by the reader. So, with higher transmitted power, the read range of these systems can be increased.

• **Backscattering Concept:**

Power that is transmitted back from the tag towards the reader is called as a backscattered power. The RFID tag antenna reflects back the electromagnetic energy to the reader antenna. There is a concept of read range in this backscattered link which is called as a reverse read range which can be calculated from above expression.



**Figure 16. Signaling in Backscatter Communication [21]**

Backscatter communication is about reflection of radio waves and especially in passive tags, tag antenna is used to gather RF energy from the reader and to communicate with it [31].

Several factors affect the amount of energy being transferred to the tag in which most important ones are:

- Transmitted Power
- Separation distance between the reader and tag
- RFID tag antenna's efficiency

The concept of impedance matching is really important in order to understand when and how the maximum amount of energy will be transferred between the reader and the tag. There are two conditions in this case; perfectly matched and not matched. The transfer of energy is maximum when the impedance of an antenna and the tag circuit is perfectly matched. On the other hand, when mismatching occurs it means that not all the power will be transferred between the reader and the tag due to the inclusion of inductive and capacitive behaviors. This leads to a shorter read range of the tag as not all the power is transmitted [32].

## 3. RFID SENSING

### 3.1 Overview

Passive RFID sensors are removing the need of extra sensors in a system. Sensing potentialities of Passive RFID systems are becoming more and more important due to their battery-free operation compared with active systems where an external power is required for operation. There are two architectures that can be used to achieve RFID sensing; one is analog sensing and the other one is digital [33]. The development of these smart RFID tags with sensing features is not opening only new research areas but also allowing the systems to be very cheap [34]. Another big advantage of using passive RFID sensors is their less maintenance and low complexity. Temperature sensing, Humidity sensing, Human monitoring, light sensing, strain sensors, biochemical sensors and several other applications exists in terms of RFID sensor tags [35]. These passive wireless sensors will not only be used for monitoring, but these environmental features can be efficiently controlled as well. Below diagram shows an infrastructure for tracking humans with or without disabilities with a main purpose to increase the convenience. This will make a smart city that is being designed for everyone as we are having diverse society in which everyone should be given an importance.



**Figure 17.** RFID with Sensor Integration for Human Detection [36]

Sensing features will provide more insight information about the product as it passes through different stages like for example in passing supply chain [4]. E-health monitoring systems are increasing day by day with advancements in sensing technologies especially, RFID sensing.

The most challenging and important part in UHF RFID systems design is to achieve higher read range and for that, power consumption of the whole system should be minimized [2].

RFID pressure sensors have numerous applications in the field of biomedical sciences where they can be implanted and used for patient health monitoring. As medical devices are becoming more and more advanced and at the same time getting expensive as well, RFID based pressure sensors are cost-effective and can be used in monitoring orthopedics and cardiovascular disease [37]. Constant measurements from this sensor in several periods of the time can be taken and used to monitor the stage of the disease. In this way, we have a monitoring system that can be used to analyze a patient's disease and health in a better and efficient manner.

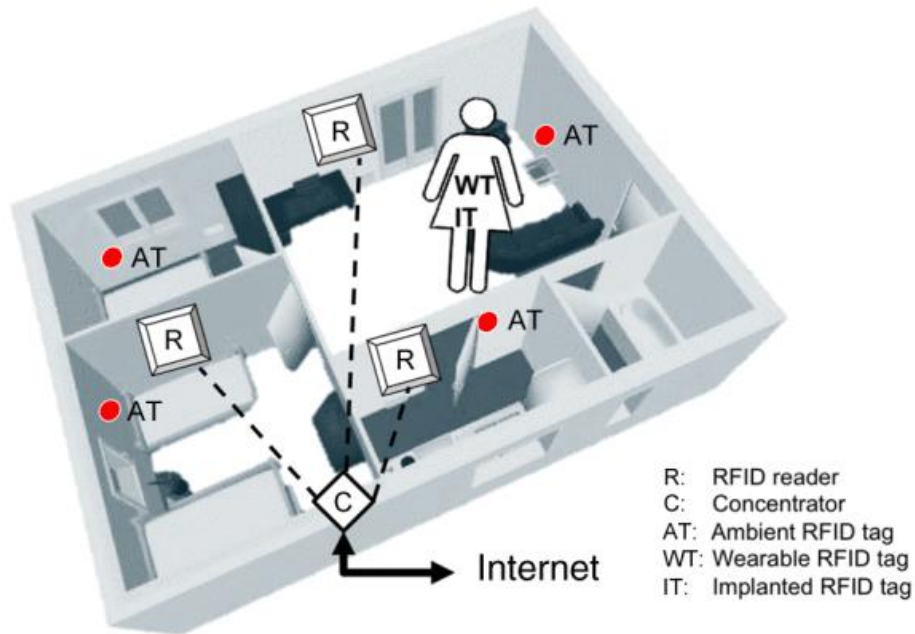
RFID pressure sensors can be implemented in the seats of public transport like in buses and airplanes where the system can be developed to count the number of passengers sitting. Integration of pressure sensors inside the sole of boots to support snowboarders to enhance their skills. The main idea behind implementing this type of sensor in wearable sports trainer is to constantly measure the activities that are performed by the users. It will eventually help in balancing the weight in order to avoid painful crashes [38].

### **3.2 RFID Sensing and IoT**

Evolution in UHF RFID has already been started from simple tracking of objects towards wireless pervasive sensing. Sensing capabilities with RFID technology will make it an important feature for future technologies, say IoT. Controlling and monitoring of several environmental features with a combination of Wireless Sensor Networks (WSN's) is now a suitable choice for IoT applications. Advancements in technology is also increasing the deployment cost. In order to implement a cost-effective sensor application, integration of RFID based sensors with IoT is very crucial.

These battery-less RFID sensors will provide a sensing network with suitable read ranges that will help in several tracking purposes involving human wellness and local environment features. Figure 16. shows a smart-home network consisting of an RFID reader communicating with several RFID tags including ambient, wearable and implanted

RFID tag. Recent research in this sector shows that the demand of passive UHF RFID sensors will increase extensively due to their passive operation and less maintenance.

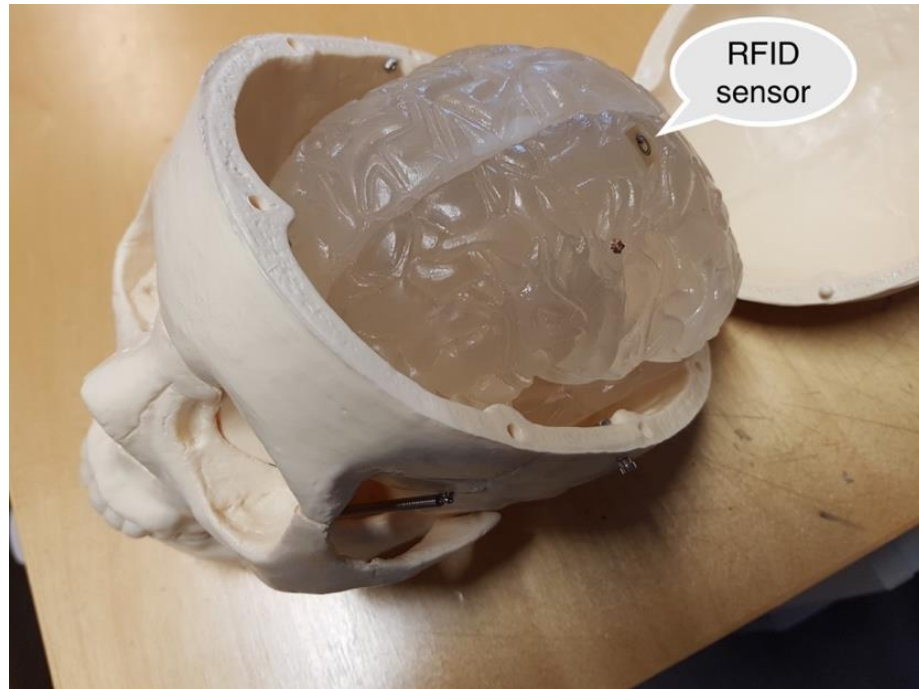


**Figure 18.** *IoT Network Based on RFID Sensing [39]*

The combination of sensing functionalities with RFID tags, new research areas are getting into the market with extensive applications including medical and health monitoring, logistics management, environment monitoring, pharmaceutical and biomedical systems [34].

### 3.3 RFID and Biosensors

Personal healthcare systems are very demanding, and they need to be efficient as well. The use of RFID technology in implantable devices as biosensors is increasing day by day. Because of their passive behavior, they are suitable devices to be integrated in humans or animals for several sensing applications including pressure sensors or temperature sensors. In previous years, low frequency (LF) and high frequency (HF) RFID systems were used but they have less ranges and low data rates. As the signals in UHF RFID bands may attenuate a lot in human body but they have higher read ranges and increased data rates compared with others [40].



**Figure 19.** *Implanted RFID Sensor in Human Brain*

Above figure is a demonstration of an implanted RFID sensor for brain health care application. To have a better treatment of intracranial disease, implantable RFID passive sensor plays an important role in preventing it [41]. Performance of a wireless system depends on various factors and it is of most importance that the communication link should be strong and the information from the sensor gets to the reader quickly.

### 3.4 Challenges

There are several challenges that should be encounter while designing RFID based sensors. First of all, they should be highly accurate, reliable, fast and small in size. As passive RFID sensors are extensively used as they operate without an external battery, so providing a strong wireless communication channel is an important concern. Another challenge that needs to be encounter here is a low-power consumption system in which we have passive RFID system that is energy efficient.

RFID pressure sensors can be used as an implantable devices where constant measurements of patient's health can be done. For this purpose, the wireless channel between the reader and the implanted sensor should be very strong so that the results achieved should be reliable. Compression of materials is an important feature as Wearable technology is coming into play day by day. So, finding the work related to this research



area was a bit difficult in the beginning but this work will provide a one step forward towards the implantation of sensor in terms of compression or pressure states.

### **3.5 Project Motivation**

Stretching and Bending are two main features that comes to our mind when we think about Wearable RFID technology. These features are studied a lot and much work is done on the behavior of RFID tag when for example stretching and bending are done. Then comes another one called 'compression' of RFID materials which we have worked on. The main motivation of starting this work as a thesis is less amount of research done in this area and to make a clear image and a step forward towards how RFID tags behave when compressed and allowed to sense in different states.

Another challenge here to encounter with was the selection of antenna that will be suitable for future RFID based sensing applications. Considering some of the previous researches, the selection of antenna was done.

## 4. MEASUREMENTS AND ANALYSIS

### 4.1 Equipment Used



(a)



(b)



(c)

**Figure 20.** Measurement Equipment (a) Anechoic Chamber (b) Voyantic Tagformance (c) Computer System Showing Results

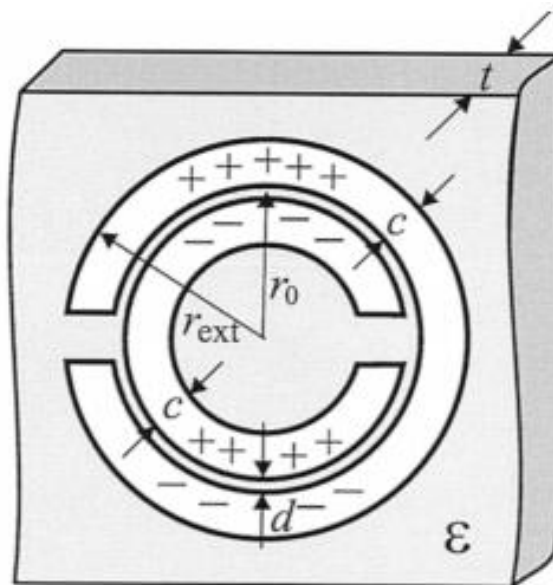
Figures above shows the anechoic chamber with Voyantic Tagformance RFID measurement system in which measurements are performed where a sensor tag is placed in front of reader antenna. The reader antenna is linearly polarized and can transmit up to 30 dBm of output power with an adjustable frequency range. Measurements were done in the range of 800-1000 MHz.

## 4.2 Antenna Development

Antenna selection is always a hard choice as it always depends on the type of application we are working on. Flexible substrate material was selected which was EPDM (Ethylene Propylene Diene Monomer) with 2mm thickness. Split Ring Resonator which is also known as SRR and two-part dipole antenna were selected and manufactured with pure copper material to check their responses separately. Since, there is some previous work which is done related to the two-part dipole antenna in terms of stretching and bending while keeping the radiating part stretchable and where feeding loop was made up of copper. Here, both the antenna parts are manufactured with copper material. Structure and dimensions of both the antennas are shown in the following sections:

### 4.2.1 Split Ring Resonator

The simple structure of SRR antenna is shown in Figure 19. The important property which SRR antenna has is negative permittivity and negative permeability which is called NMPM [42]. These NMPM are basically used to make materials like SRR which can have two parts with one the radiating part and the other one as feeding loop in terms of RFID systems.



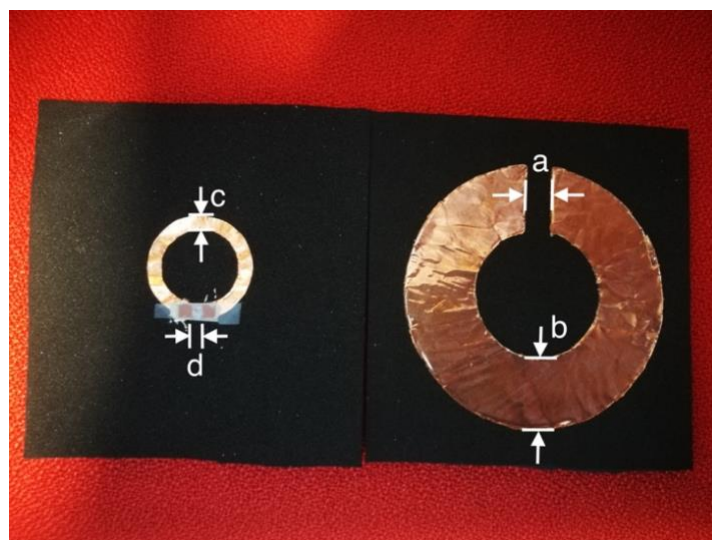
**Figure 21.** Structure of SRR [42]



**Figure 22.** Split Ring Array to Build Meta-Materials [43]

The designed SRR with its geometry and the dimensions of the SRR antenna is shown in figure 21. There are two concentric rings having a split gap between them. For the feeding loop part, IC is attached in that gap.

SRR works in this way that the time varying magnetic field which is perpendicular to the plane of the SRR antenna induces current in the feeding part of the antenna. The induction of current on the feeding loop because of this time varying magnetic field results in a magnetic field coming out from the inner part of the inner ring to its outer part. These split gaps in the rings results in the generation of opposite directional current in the outer part (radiating part) of the SRR [44].



**Figure 23.** Designed SRR [44]

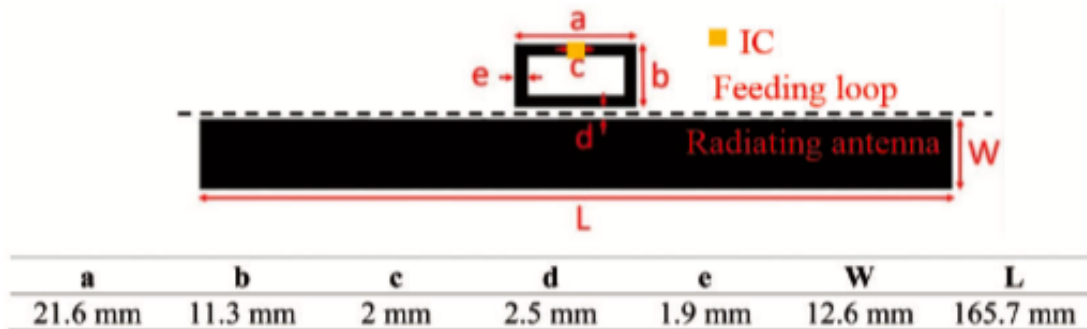
<i>Geometry</i>	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
	6.6 mm	16.1 mm	2.8 mm	2 mm

**Table 2.** Geometry Parameters of Designed SRR

#### 4.2.2 Two-Part Dipole Antenna

Dipole antennas are one of most commonly used antenna specifically for RFID applications. As from its name, it is clear that it consists of two terminals in which current flows. The distribution of voltage and current varies along the length of the radiating part of an antenna. There occurs peaks and troughs because of the set-up of standing wave along the length of a radiating part. The working principle of two-part dipole antenna is same as of a simple dipole antenna. Here, the feeding loop is connected with IC chip and the radiating part is separate as designed in SRR antenna. When considering wearable technology application, two-part antennas designs can show better results as bending, stretching and compression are key properties in it [45].

Figure shown below is taken from a previous work related to the fabrication of wearable RFID tags. Same parameters have been used in this research work but here only a copper material is used to make both the radiating and the feeding loop of an antenna:



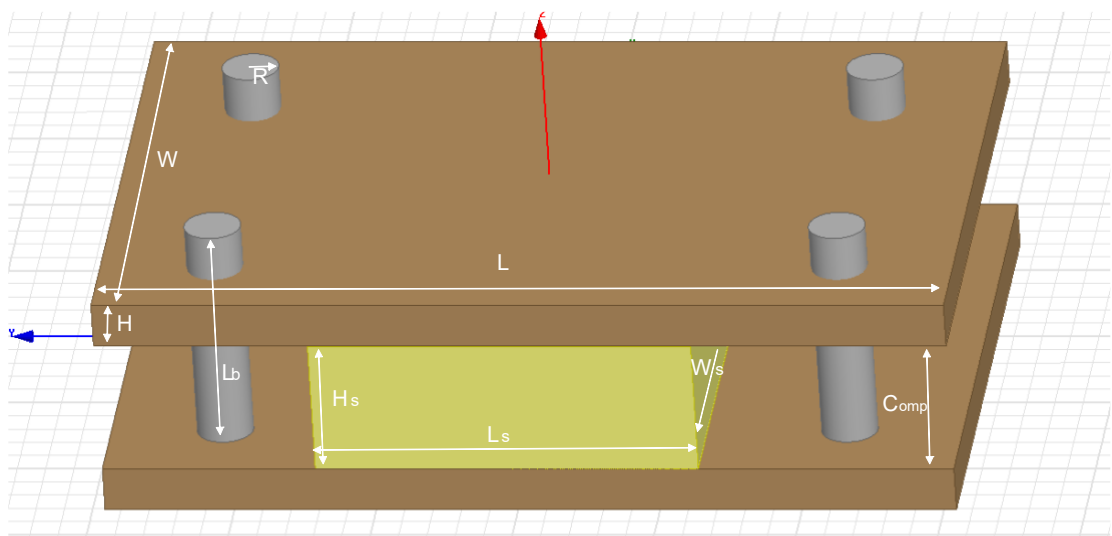
**Figure 24.** Parameters of Two-Part Dipole Antenna [45]



*Figure 25. Designed Two-part Dipole Antenna*

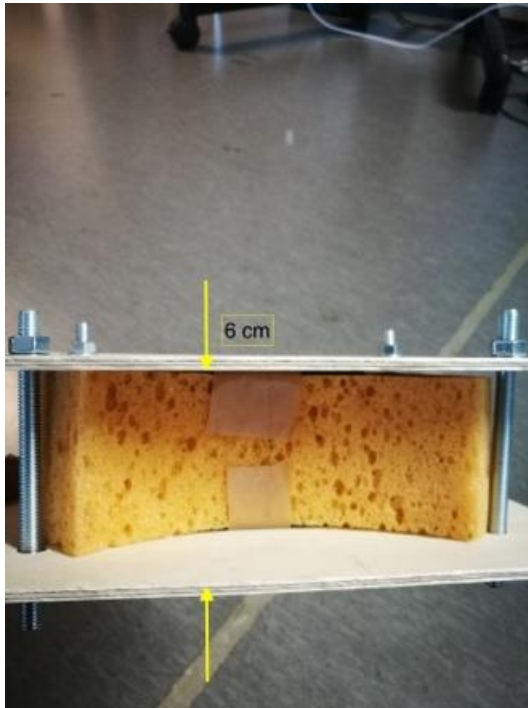
### 4.3 Different States of Measurements

Both, SRR and two-part dipole antennas were manufactured and tested with different levels of compression. The structure shown below is a 3D diagram of the sensor setup that was created. Yellow color is representing the sponge on which the sensor tag was placed and then the brown color shows the plywood.

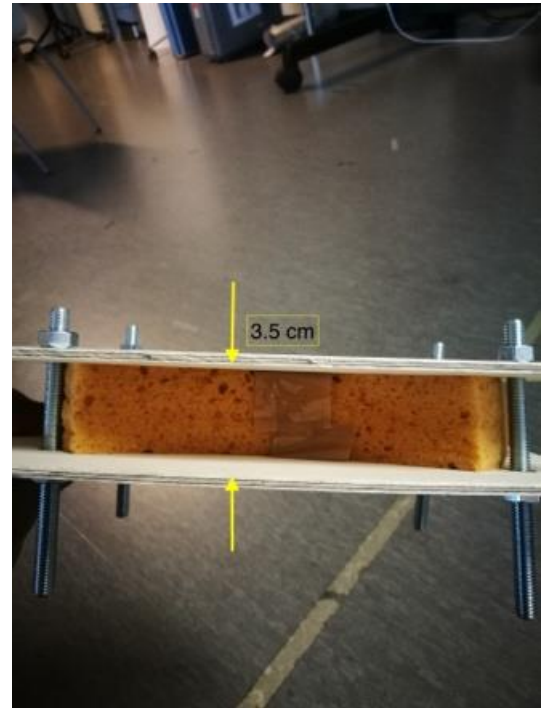


*Figure 26. 3D Structure of a Sensor Setup*

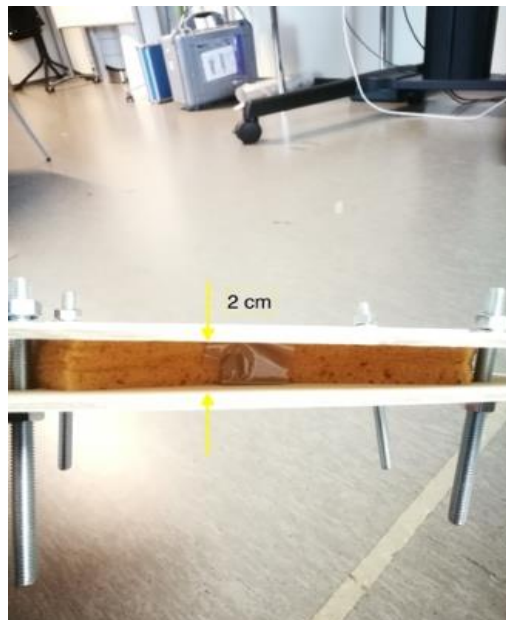
Three of the following compression states of our sensor tags were tested to check their response in terms of read range and backscattering power.



(a)



(b)



(c)

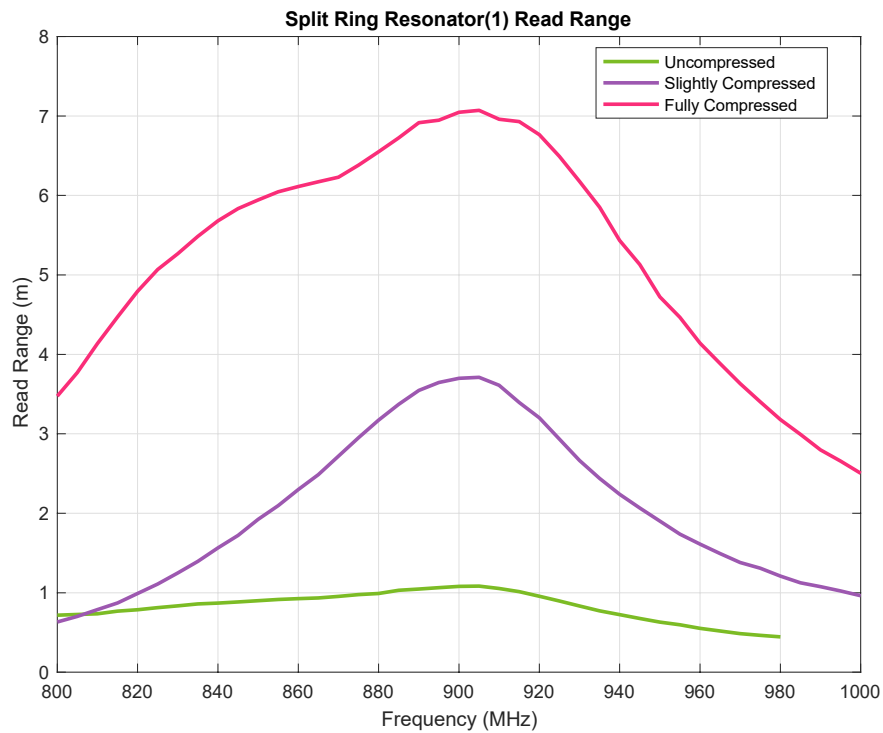
**Figure 27.** (a) Uncompressed (b) Slightly Compressed (c) Fully Compressed



### 4.3.1 Compression for Split Ring Resonator

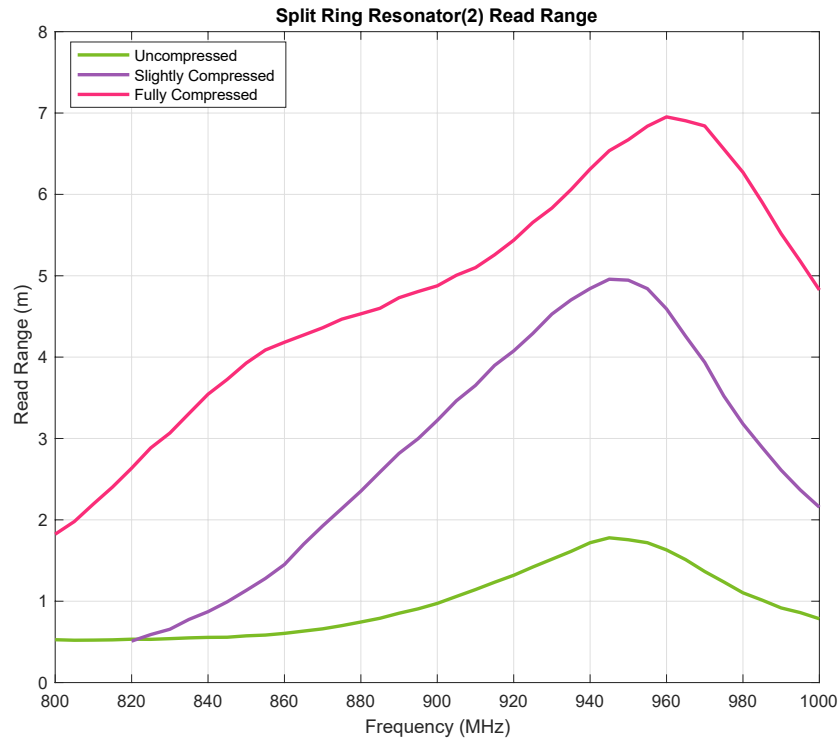
Three SRR antennas were designed with same geometries and then tested to see their response when they are subjected to compression. All of the three almost showed the same behavior, as read range was increased when they were slightly compressed and fully compressed compared with a state when they were uncompressed. There might be some uncertainties while performing compression as alignment between both antenna parts might be gone a bit wrong that might have affected the graph of read ranges.

Below are read range versus frequency graphs for sensor tags with SRR antenna in three of the compression states:

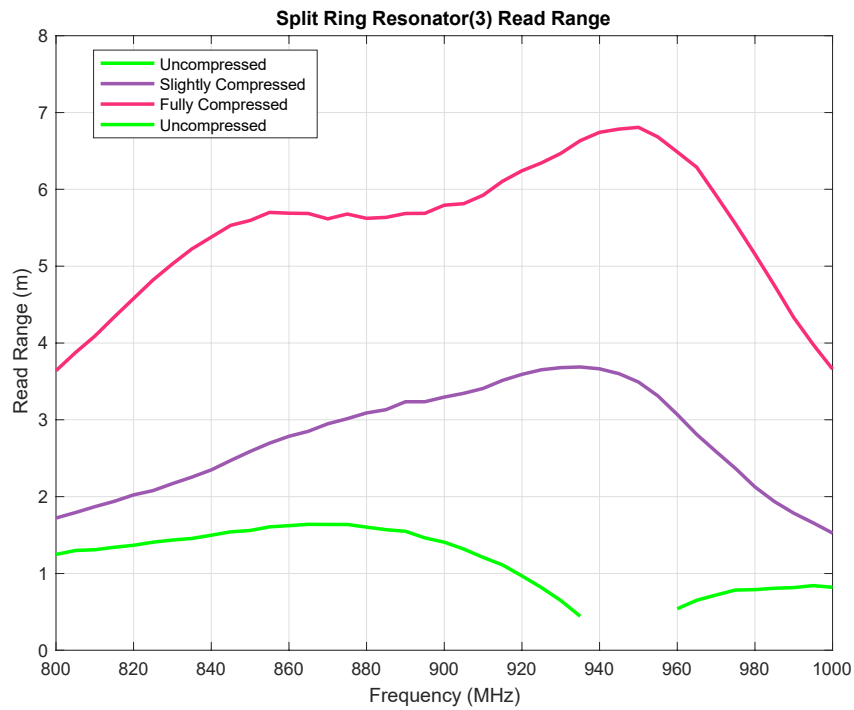


**Figure 28.** *SRR1 Read Range*





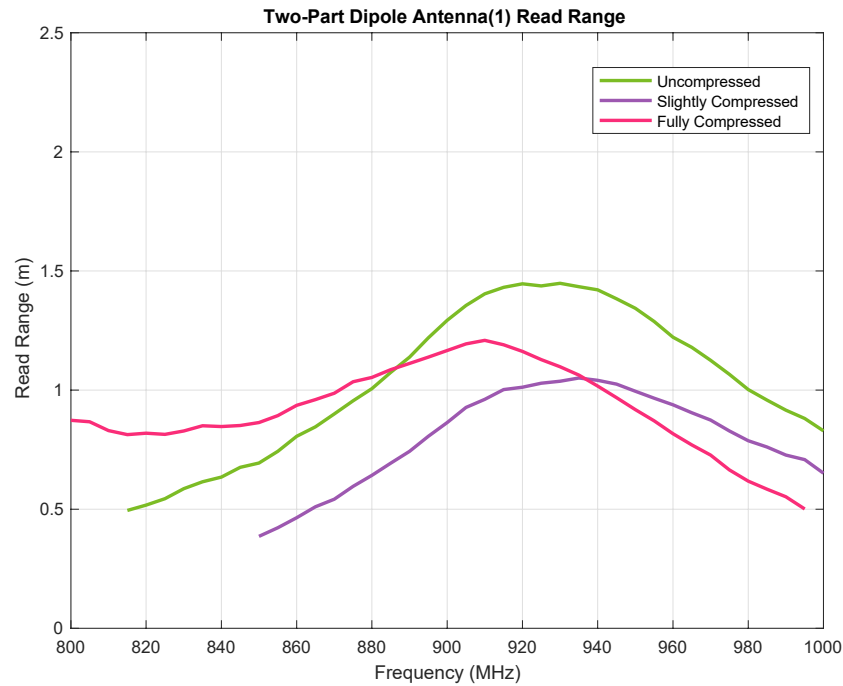
**Figure 29. SRR2 Read Range**



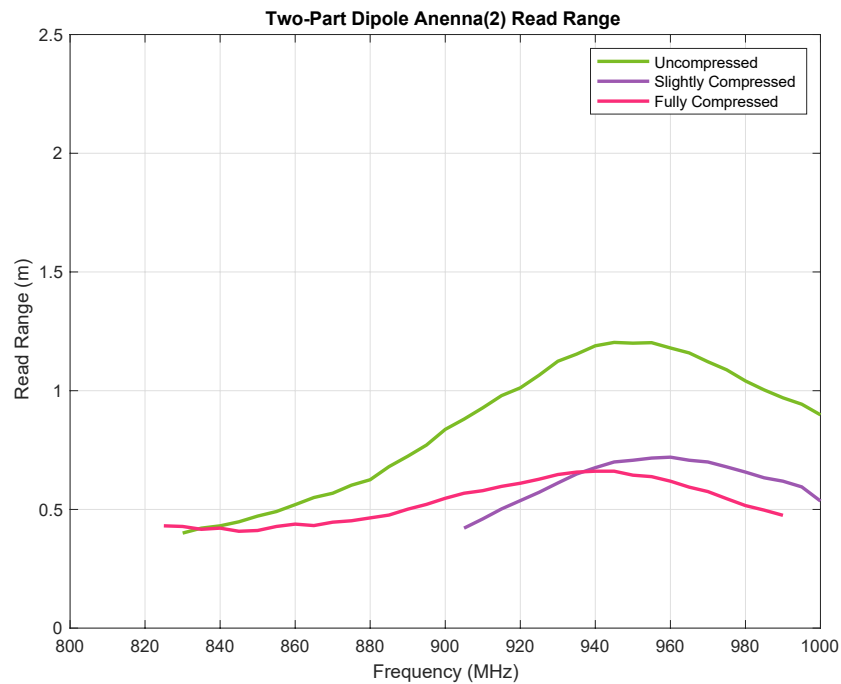
**Figure 30. SRR3 Read Range**

### 4.3.2 Compression for Two-Part Dipole Antenna

Similarly, the same read range measurements were performed in case of two-part dipole antennas in their compression states. The same structure was used, and the same level of compressions were provided. Both parts were first placed away from each other on the both sides of sponge with a separation distance of 6 cm. Figures below shows the results:



*Figure 31. Read Range of Dipole1*



*Figure 32. Read Range of Dipole2*

Tables below shows the difference between the read ranges of Split Ring Resonator and two-part dipole antenna; values taken at a specific frequency level to see the response and to make a clear comparison out of it:

	<i><b>SRR1</b></i>	<i><b>SRR2</b></i>	<i><b>SRR3</b></i>
<i><b>Parameter</b></i>	<i><b>Read Range</b></i>	<i><b>Read Range</b></i>	<i><b>Read Range</b></i>
<i><b>Frequency (920 MHz)</b></i>			
<i><b>States:</b></i>			
<i>Uncompressed</i>	<i>0.9 m</i>	<i>1.2 m</i>	<i>0.9 m</i>
<i>Slightly Compressed</i>	<i>3.6 m</i>	<i>4.1 m</i>	<i>3.6 m</i>
<i>Fully Compressed</i>	<i>7.1 m</i>	<i>5.4 m</i>	<i>6.2 m</i>

**Table 3.** Read Range of Split Ring Resonator Antenna

	<i><b>Dipole1</b></i>	<i><b>Dipole2</b></i>
<i><b>Parameter</b></i>	<i><b>Read Range</b></i>	<i><b>Read Range</b></i>
<i><b>Frequency (920 MHz)</b></i>		
<i><b>States:</b></i>		
<i>Uncompressed</i>	<i>1.4 m</i>	<i>1.0 m</i>
<i>Slightly Compressed</i>	<i>1.0 m</i>	<i>0.5 m</i>
<i>Fully Compressed</i>	<i>1.8 m</i>	<i>0.6 m</i>

**Table 4.** Read Range of Two-part Dipole Antenna

### 4.3.3 Reference Tag Insertion

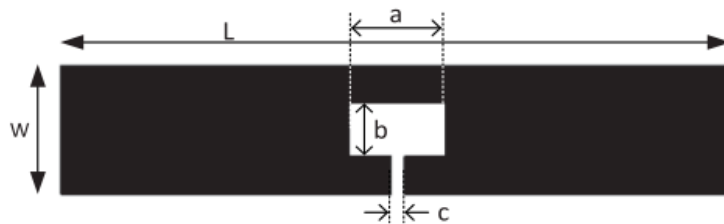
Another tag as a reference tag (with dipole antenna) was also placed inside the anechoic chamber with our sensor tag to check how does it affects the measurements of our sensor. The behavior of sensor tag almost remained same, but it affected the required power level to turn it on. We measured backscattering power in six compression states (6 cm, 5 cm, 4 cm, 3 cm, 2 cm, and 1 cm).



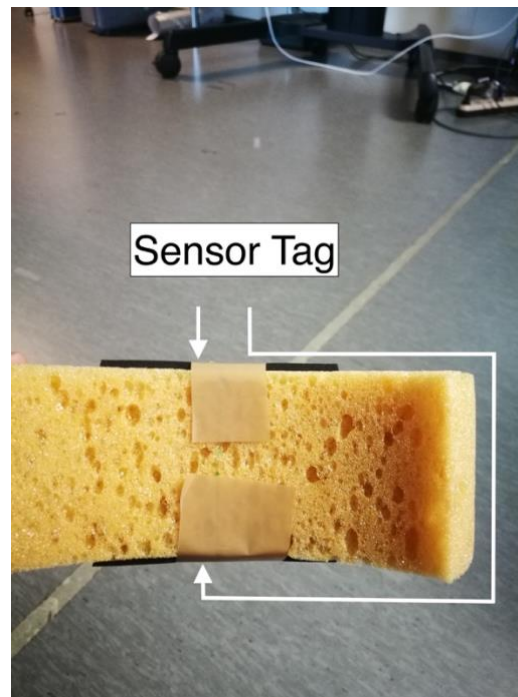
*Figure 33. Reference Tag Insertion*

Geometrical parameters in millimeters

$L$	$W$	$a$	$b$	$c$
100	20	14.3	8.125	2

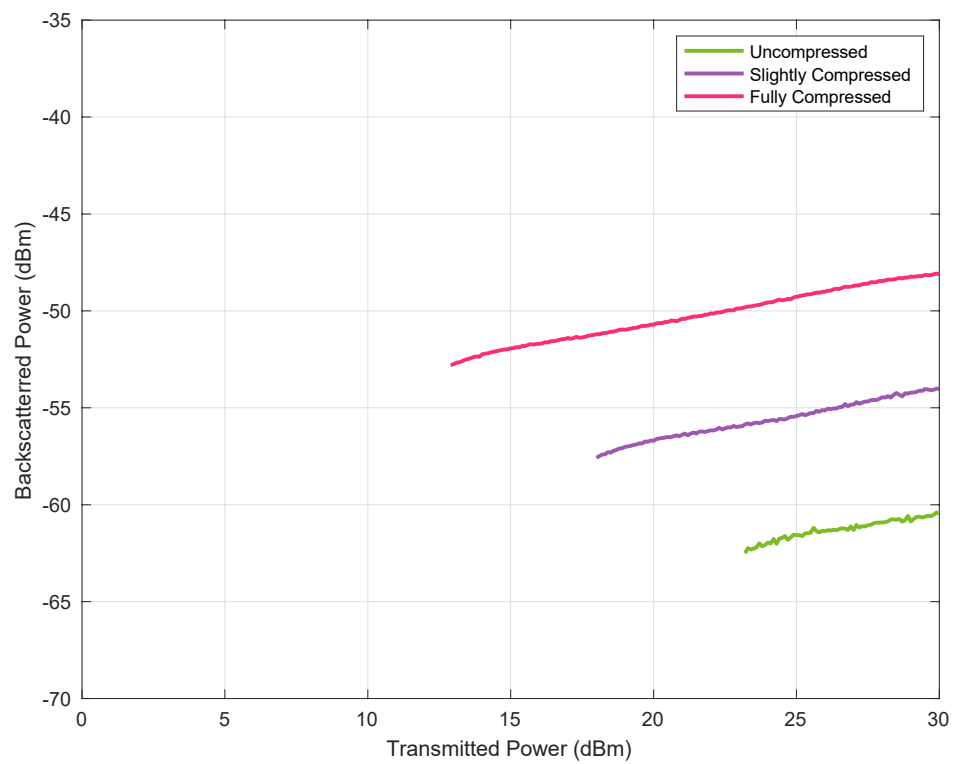


*Figure 34. Reference Tag with Parameters [46]*



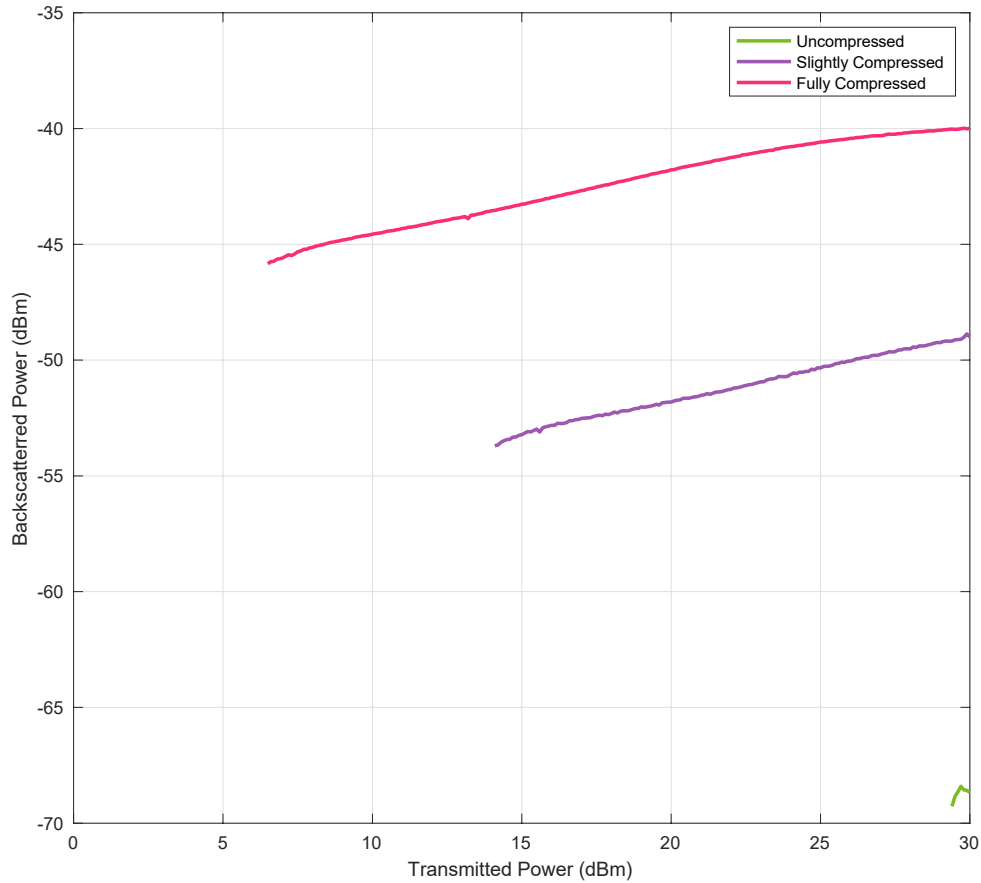
*Figure 35. Sensor Tag*

**SRR Backscattering Measurement:**



*Figure 36. SRR1 Backscattered Power*

Backscattering measurements were also performed on sensor tag with SRR antenna to further analyze the behavior of the sensor. Figures for backscattering power shows that sensor tag is taking less power to get activate when it is in fully compressed state compared with other two states when it is uncompressed and slightly compressed. As in fully compressed case, both antenna parts are very close to each other, the response from sensor tag is quick and it takes less power to turn on the IC.

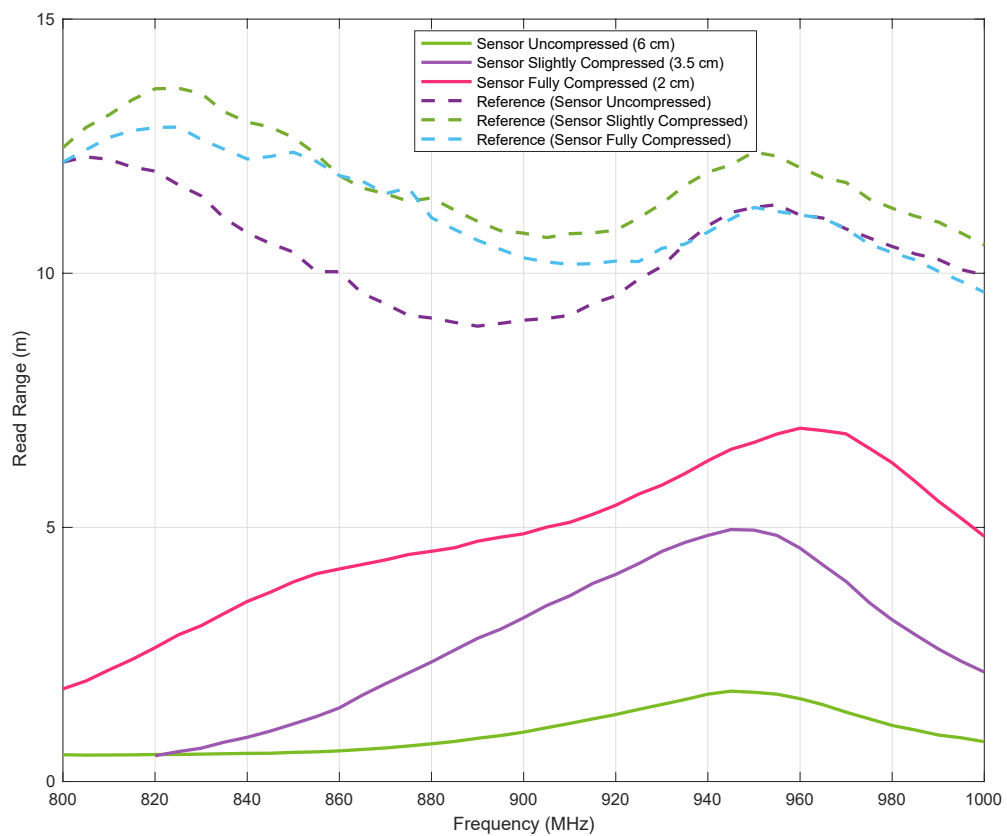


**Figure 37. SRR2 Backscattered Power**

The table below shows the turn on power for the sensor with SRR1 and SRR2 in three states. As said, the maximum transmitter power here is 30 dBm and in the case of uncompressed state, the turn on power is highest. Contrary to the fully compressed situation, it takes really less power to start giving a response which is 12.9 dBm in case of SRR1 and 6.5 dBm for SRR2. Here it is very clear to extract that when both the antenna parts are close to each other, the sensor takes less power to turn on which actually proves the compression level indicator case.

	<i>SRR1</i>	<i>SRR2</i>
<i>Compression States</i>	<i>Turn on Power</i>	<i>Turn on Power</i>
<i>Uncompressed</i>	23.2 dBm	29.4 dBm
<i>Slightly Compressed</i>	18.0 dBm	14.1 dBm
<i>Fully Compressed</i>	12.9 dBm	6.5 dBm

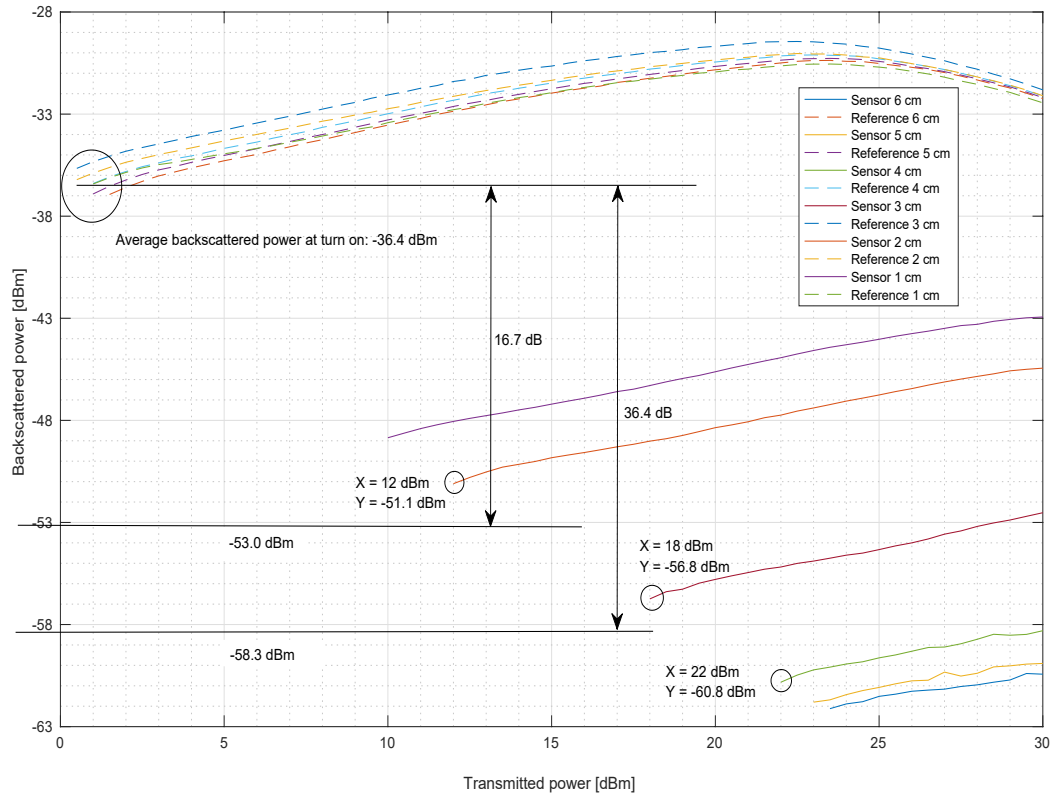
**Table 5.** Turn on Power (Sensor with SRR)



**Figure 38.** Read Range Comparison of Sensor and Reference Tag

The RF Transmitter used in these measurements is assumed to be an adjustable power source. In this approach, the threshold power of the reference and sensor tag is recorded which is marked in figure 33.

The comparison between the backscattered signals for both the sensor and the reference tag is measured.



**Figure 39.** Backscattering Comparison of Sensor and Reference Tag

## 4.4 Analysis

The main target of this research was to analyze the performance of a sensor tag in three different compression states in order to see how their read range changes and how much backscattering power we get from it. This compression actually comes under pressure sensing applications. Both of these parameters are separately analyzed below:

### 4.4.1 Read Range Analysis

Read range of an RFID tag is a maximum distance at which a tag can be detected, and the reader starts getting response from it. There were three compression states that were



applied to the sensor tag, and the read range was measured accordingly. As said, two different types of antennas were tested under these conditions in order to check which one is suitable in our case.

SRR showed the best results as the read range was increased when both the antenna parts were brought close to each other. Similarly, our sensor tag required less power to turn on and it started giving response with a very less power when it was in fully compressed state. Two-part dipole antenna showed an abnormal response when it's both parts were away and close to each other which can be clearly seen from the read range figures of dipole antennas.

#### **4.4.2 Backscattering Power Analysis**

The threshold power level is recorded for both the reference and the sensor tag in order to analyze both of them in a same state where the chips of these tags are operating in a same condition. Backscattered power response from the reference was almost same in all the measurements stages while the sensor tag was being compressed. Averaged backscattered power for the reference tag to turn on is taken to be -36.4 dBm. Our sensor tag required less power to turn on and it started giving response with a very less power when it was in fully compressed state, which means that the backscattered power transmitted by the sensor is highest in the state when it was compressed to full extent. The response of sensor in fully compressed state is 16.7 dB or less below the reference value. In an uncompressed state, the sensor's response is 36.4 dB or more below the reference. In the intermediate state where the sensor was slightly compressed, the response from the sensor is 36.4 dB below the reference level which is actually much more than that in fully compressed state.

## 5. CONCLUSION

The focus of this research was to design a new type of a sensor tag that detects the compression level for passive RFID tags comprising of different antennas. Two different antennas, Two-part dipole antenna and SRR antenna were designed to evaluate their performance in different compression states. Both of these were designed with a copper conducting material with an EPDM (Ethylene Propylene Diene Monomer) substrate. Both antennas have two conducting parts. In case of SRR, IC is connected to the smaller (inner) part of an antenna and in case of two-part dipole antenna, RFID IC is attached to the feeding loop which is a smaller part of an antenna.

Three compression states were tested initially with sensor tag in order to evaluate its performance. Both antennas were subjected to different compression states to confirm a principle that read range should increase as both the antenna parts are close to each other. SRR antenna comes out to be a successful choice to implement it in this way because it's read range was increased when subjected to compression. Two more SRR antennas were designed with same parameters to further confirm these results and they showed the same behavior as well. Contrary to that, two-part dipole antennas showed an abnormal behavior and their read range was not increased when both antenna parts were compressed and made close to each other. So, performing compression on various tags with two-part dipole antenna and SRR antenna, a sensor tag with SRR antenna came out to be a successful choice in compression sensing applications.

Backscattering analysis was also performed with this sensor tag having an SRR antenna. In terms of backscattering, SRR showed good results as well. As the antenna parts of sensor tag were brought near with compression, sensor starts taking a less power to give a response back to reader. So, a conclusion came that when a material is in fully compressed state, it takes less power to activate a sensor. The use of RFID based sensors is increasing with Wireless Sensor Networks and IoT where several devices will communicate with each other in order to provide ease to all users.

Here, a reference tag with a single-part dipole antenna manufactured with a pure copper material was also inserted in anechoic chamber with a sensor tag to check and compare the behavior of sensor and reference tag and how they are affected with each other. Another benefit of using a reference tag could be that if in future we have a network of several sensors, then this reference tag can be used as a reference and comparisons can easily be made with the help of it. The behavior of both, the sensor and reference tag remained same but as there were two tags in measurement chamber at the same time so, the transmitted power should be divided among these tags as both needs power to give a response due to their passive behavior.

In future, this research can be used for system optimization for various antennas in wearable technology facing compression levels. Here, pure copper material was used for antenna development but in future considering, conductive fabric (copper nickel) can be used and its performance at different compression levels can be checked and compared with this research work.

As this RFID based passive sensor is a battery free device and less maintenance is required for it to operate properly, these are very effective choice for compression sensing areas like structural health monitoring (SHM).

## 6. PUBLICATION

1. Shoaib Tahir Qureshi, Toni Björninen, Johanna Virkki, “Referenced backscattering compression level indicator based on passive UHF RFID tags,” accepted in IEEE RFID-TA 2018.

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